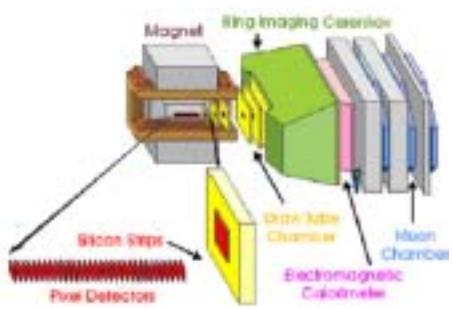
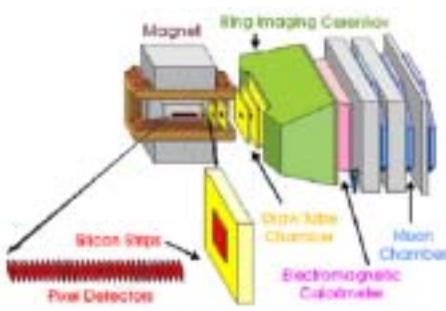


S. Stone
Sept, 2002



An Introduction to the Physics of $BTeV$ & Implications for the Detector



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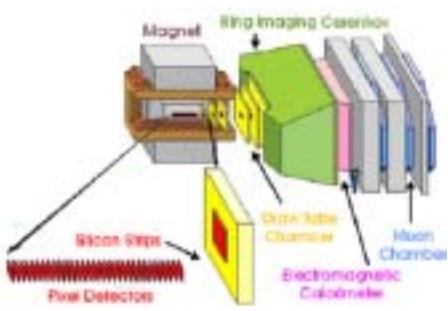
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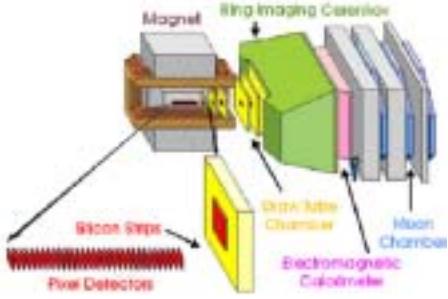
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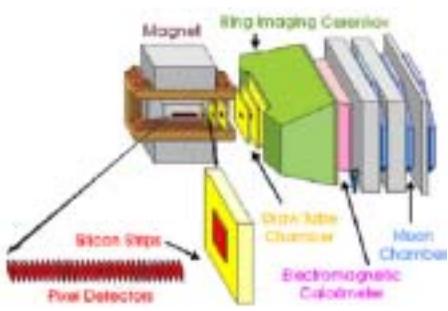
Physics Goals

- ◆ Discover or set stringent limits on “New Physics,” from b & c decays
- ◆ “New Physics” is needed for several reasons
 - ◆ Hierarchy Problem – *SM can't explain smallness of weak scale compared to GUT or Planck scales*
 - ◆ Plethora of “fundamental parameters,” *i.e. quark masses, mixing angles, etc...*
 - ◆ SM CP parameter not large enough to explain baryon asymmetry of the Universe-*should see new effects in b and/or c decays*



Physics Goals

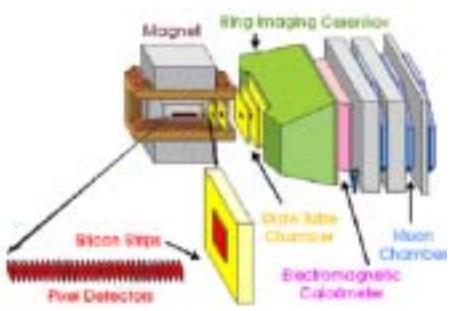
- ◆ When we find “New Physics” we need to probe it, to find out what it really is – connections with direct searches at high energy
- ◆ Measure Standard Model parameters, such as the CP violating angles



Quark Mixing & the CKM Matrix

$$V = \begin{pmatrix} u & d & s & b \\ c & -\lambda & 1 - \frac{1}{2}\lambda^2 - i\eta A^2 \lambda^4 & A\lambda^2(1 + i\eta\lambda^2) \\ t & A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

- ◆ A, λ, ρ and η are in the Standard Model fundamental constants of nature like G , or α_{EM}
- ◆ η multiplies i and is responsible for CP violation
- ◆ We know $\lambda=0.22$, $A\sim 0.8$; constraints on ρ & η



The 6 CKM Triangles

$$\begin{matrix} \textbf{ds} \\ \chi' \\ V_{cd}V_{cs}^* \\ V_{ud}V_{us}^* \\ V_{td}V_{ts}^* \end{matrix}$$

$$\begin{matrix} \textbf{uc} \\ V_{ub}V_{cb}^* \\ V_{ud}V_{cd}^* \\ V_{us}V_{cs}^* \end{matrix}$$

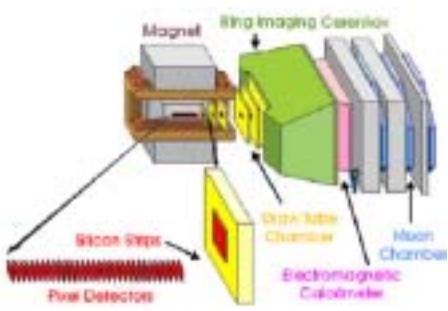
$$\begin{matrix} \textbf{sb} \\ \chi \\ V_{ts}V_{tb}^* \\ V_{cs}V_{cb}^* \\ V_{us}V_{ub}^* \end{matrix}$$

$$\begin{matrix} \textbf{ct} \\ V_{cd}V_{td}^* \\ V_{cs}V_{ts}^* \\ V_{cb}V_{tb}^* \end{matrix}$$

$$\begin{matrix} \textbf{bd} \\ V_{ub}V_{ud}^* \\ V_{cb}V_{cd}^* \\ \gamma \\ \alpha \\ V_{tb}V_{td}^* \\ \beta \end{matrix}$$

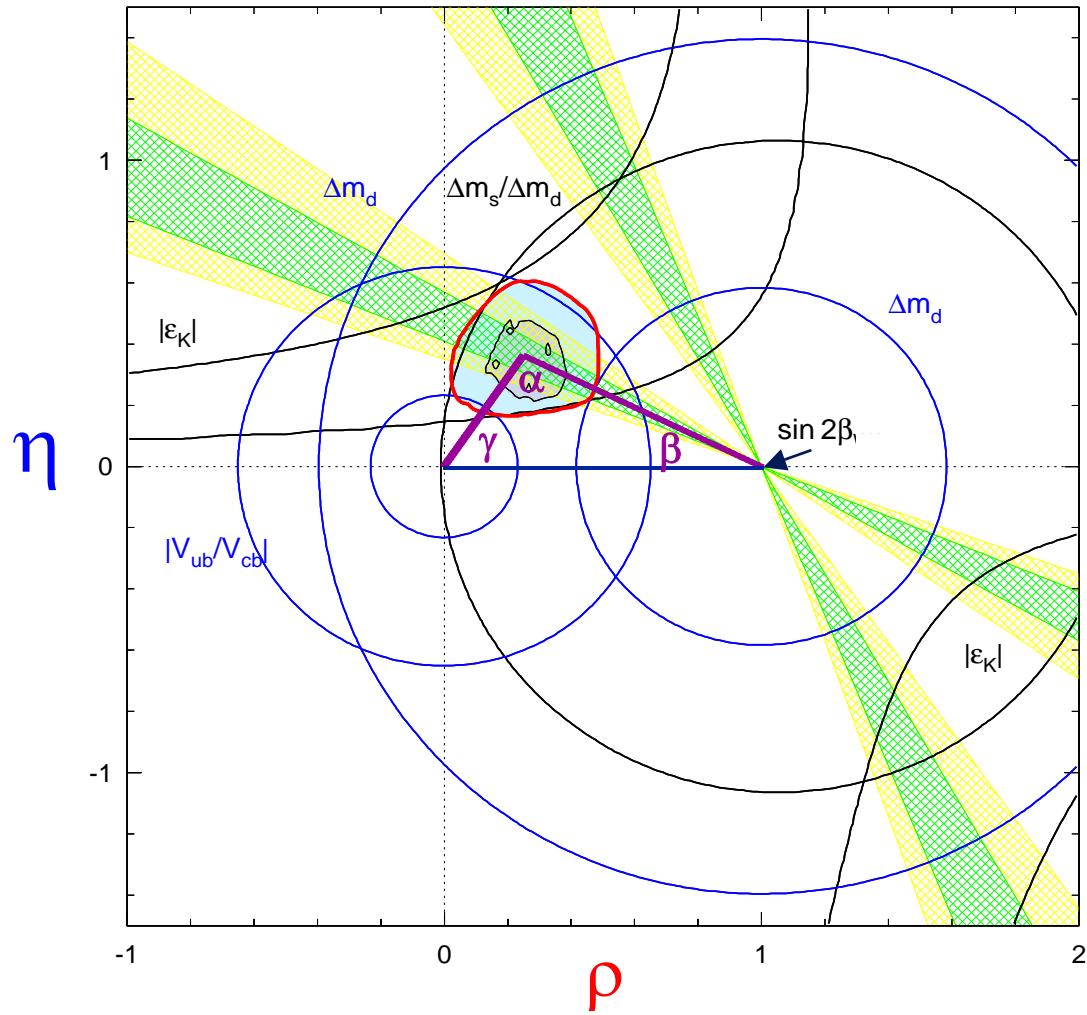
$$\begin{matrix} \textbf{tu} \\ V_{ts}V_{us}^* \\ V_{td}V_{ud}^* \\ V_{tb}V_{ub}^* \end{matrix}$$

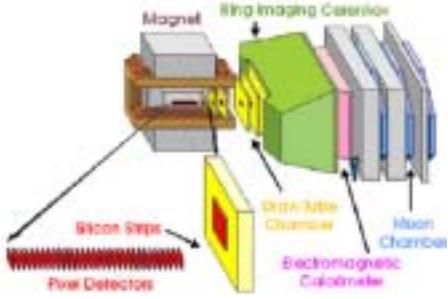
- ◆ From Unitarity
- ◆ “ds” - indicates rows or columns used
- ◆ There are 4 independent phases, which can be used to construct entire CKM matrix: $\beta, \gamma, \chi, \chi'$



Current Status

- ◆ Constraints on ρ & η from Artuso using Hocker et al.
- ◆ Theory parameters are allowed to have equal probability within a restricted but arbitrary range
- ◆ Therefore large model dependence for V_{ub}/V_{cb} , ε_K and Δm_d , smaller but significant for Δm_s and virtually none for $\sin(2\beta)$



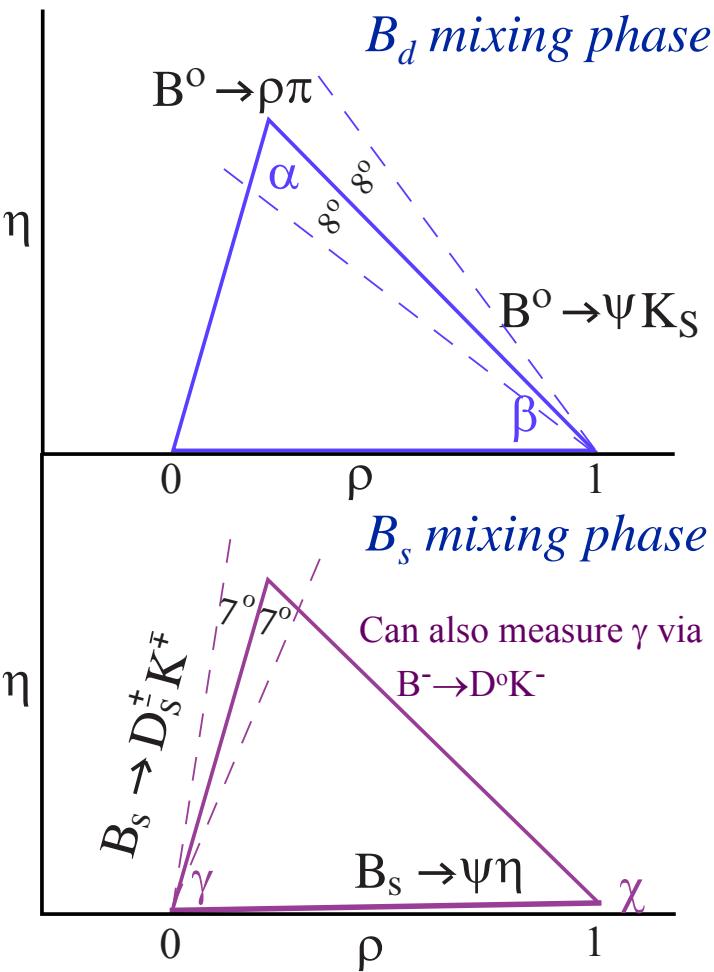
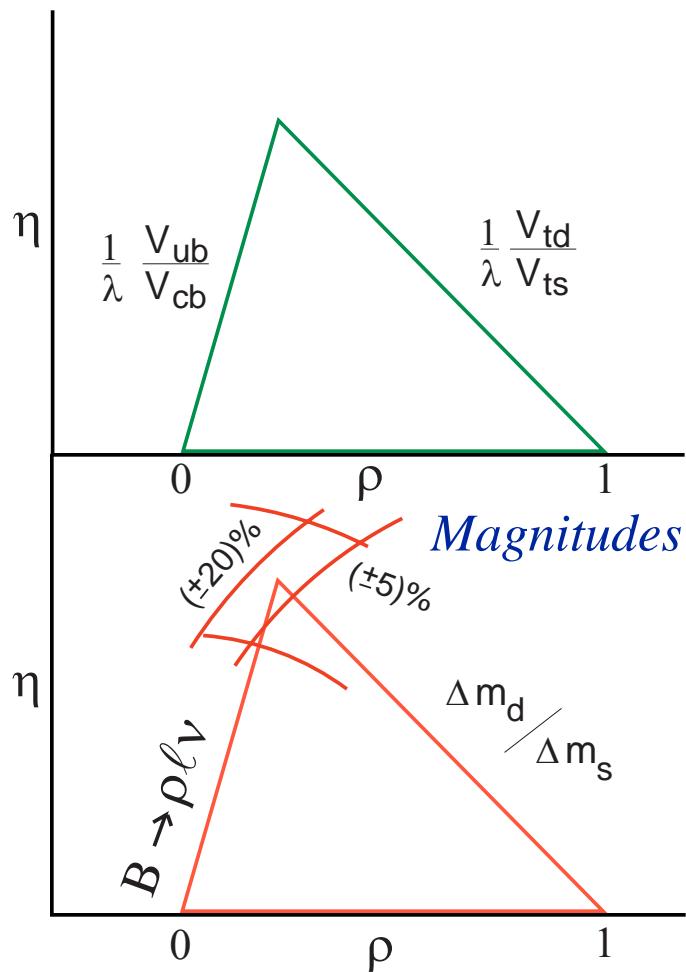


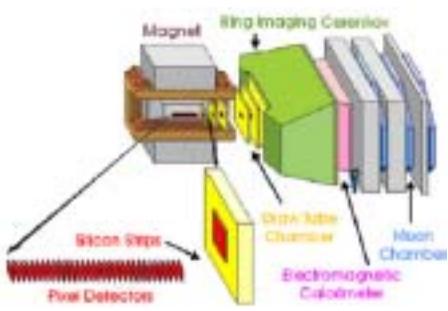
Separate Checks

- ◆ Use different sets of measurements to define apex of triangle

(from Peskin)

- ◆ Also have ε_K (\not{CP} in K_L system)



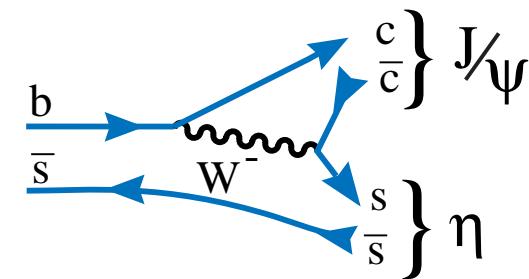


Critical Checks using χ

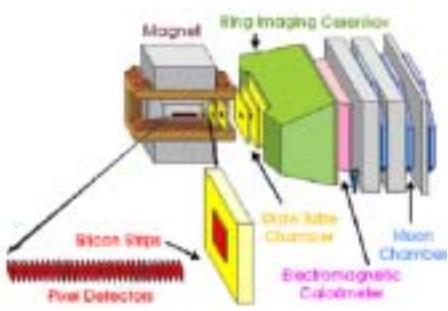
- ◆ Silva & Wolfenstein (hep-ph/9610208), (Aleksan, Kayser & London), propose a test of the SM, that can reveal new physics; it relies on measuring the angle χ .

- ◆ BTeV can use CP eigenstates in B_s decay to measure χ , for example $B_s \rightarrow J/\psi \eta^{(\prime)}$, $\eta \rightarrow \gamma\gamma$, $\eta' \rightarrow \rho\gamma$
- ◆ Can also use $J/\psi \phi$, but need a complicated angular analysis
- ◆ The critical check is

$$\sin \chi = \lambda^2 \frac{\sin \beta \sin \gamma}{\sin(\beta + \gamma)}$$

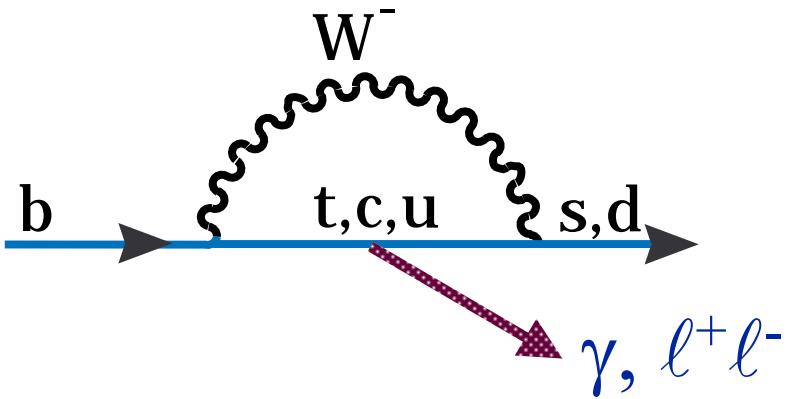


- ◆ Very sensitive since $\lambda = 0.2205 \pm 0.0018$
- ◆ Since $\chi \sim 0.03$, need lots of data

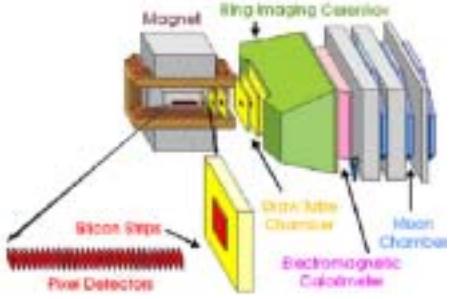


Rare b Decays

- ◆ A good place to find new physics

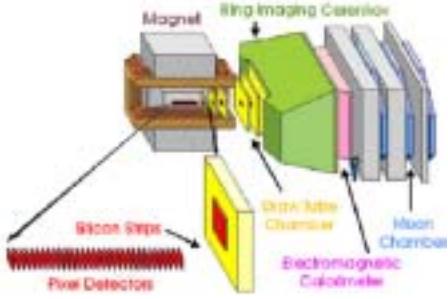


- ◆ New fermion like objects in addition to t, c or u
- ◆ Exclusive Rare Decays such as $B \rightarrow \rho\gamma$, $B \rightarrow K^* \ell^+ \ell^-$: Dalitz plot & polarization
- ◆ Inclusive Rare Decays such as inclusive $b \rightarrow s\gamma$, $b \rightarrow d\gamma$, $b \rightarrow s\ell^+ \ell^-$



Generic Tests for New Physics

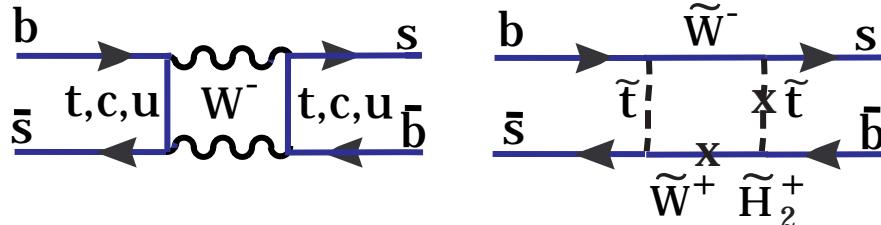
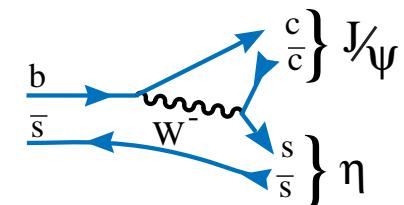
- ◆ Specific decays, non-specific models (example)
 - ◆ $B \rightarrow K\ell^+\ell^-$ & $B \rightarrow K^*\ell^+\ell^-$ effects on dilepton invariant mass & Dalitz plot. “*Especially the decay into K^* yields a wealth of new information on the form of the new interactions since the Dalitz plot is sensitive to subtle interference effects*” (Greub, Ioannissian & Wyler hep-ph/9408382)
- ◆ Another idea is to test for inconsistencies in SM predictions, independent of specific non-standard model



MSSM Measurements from Hinchcliff & Kersting

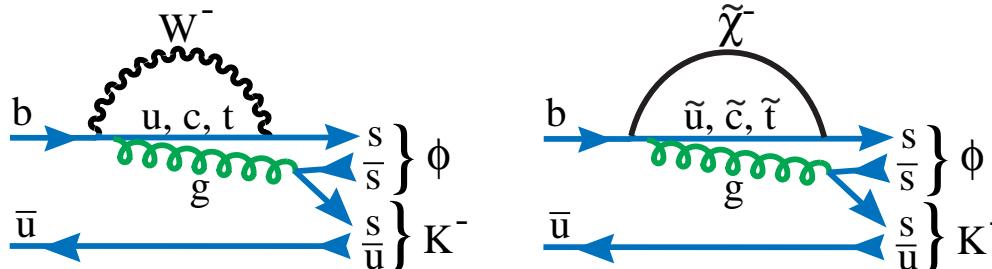
(hep-ph/0003090)

◆ Contributions to B_s mixing

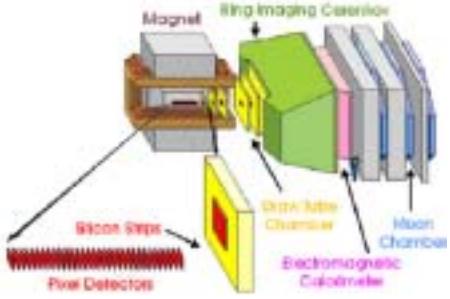

 $B_s \rightarrow J/\psi \eta$


CP asymmetry $\approx 0.1 \sin\phi_\mu \cos\phi_A \sin(\Delta m_s t)$, $\sim 10 \times$ SM

◆ Contributions to direct CP violating decay

 $B^- \rightarrow \phi K^-$


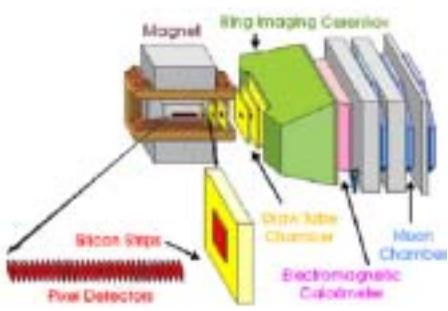
Asym = $(M_W/m_{\text{squark}})^2 \sin(\phi_\mu)$, ~ 0 in SM



Summary of New Physics

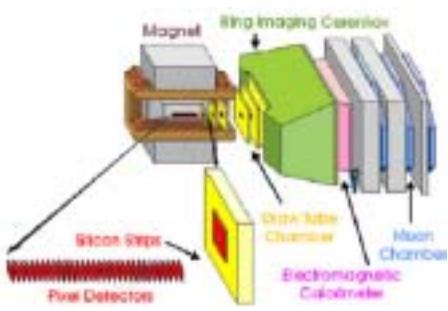
- ◆ We are sensitive using b and c decays in loop diagrams to mass scales \sim few TeV depending on couplings (model dependent). The New Physics effects in these loops may be the only way to distinguish among models.
- ◆ Masiero & Vives: *“the relevance of SUSY searches in rare processes is not confined to the usually quoted possibility that indirect searches can arrive ‘first’ in signaling the presence of SUSY. Even after the possible direct observation of SUSY particles, the importance of FCNC & CPV in testing SUSY remains of utmost relevance. They are & will be complementary to the Tevatron & LHC establishing low energy supersymmetry as the response to the electroweak breaking puzzle”* (hep-ph/0104027)

We agree, except we would replace “SUSY” with “New Physics”



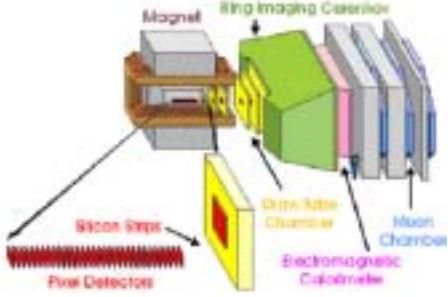
Summary of required measurements for CKM tests

Physics Quantity	Decay Mode	Vertex Trigger	K/π sep	γ det	Decay time σ
$\sin(2\alpha)$	$B^0 \rightarrow \rho\pi \rightarrow \pi^+\pi^-\pi^0$	✓	✓	✓	
$\sin(2\alpha)$	$B^0 \rightarrow \pi^+\pi^-$ & $B_s \rightarrow K^+K^-$	✓	✓		✓
$\cos(2\alpha)$	$B^0 \rightarrow \rho\pi \rightarrow \pi^+\pi^-\pi^0$	✓	✓	✓	
$\text{sign}(\sin(2\alpha))$	$B^0 \rightarrow \rho\pi$ & $B^0 \rightarrow \pi^+\pi^-$	✓	✓	✓	
$\sin(\gamma)$	$B_s \rightarrow D_s K^-$	✓	✓		✓
$\sin(\gamma)$	$B^0 \rightarrow D^0 K^-$	✓	✓		
$\sin(\gamma)$	$B \rightarrow K \pi$	✓	✓	✓	
$\sin(2\chi)$	$B_s \rightarrow J/\psi \eta', J/\psi \eta$		✓	✓	✓
$\sin(2\beta)$	$B^0 \rightarrow J/\psi K_s$				
$\cos(2\beta)$	$B^0 \rightarrow J/\psi K^*$ & $B_s \rightarrow J/\psi \phi$		✓		
x_s	$B_s \rightarrow D_s \pi^-$	✓	✓		✓
$\Delta\Gamma$ for B_s	$B_s \rightarrow J/\psi \eta', K^+K^-, D_s \pi^-$	✓	✓	✓	✓



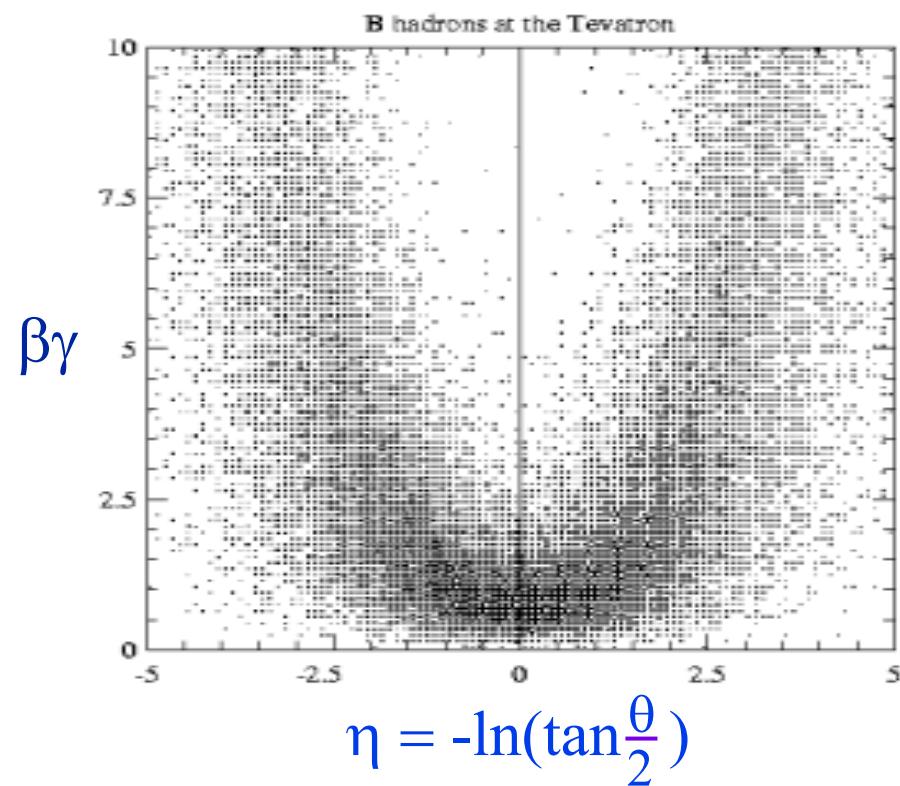
Why do b & c decay physics at the Fermilab Tevatron?

- ◆ Large samples of b quarks are available, with the Main Injector, the collider will produce $\sim 4 \times 10^{11}$ b hadrons per 10^7 sec at $L = 2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$.
- ◆ e^+e^- machines operating at the Y(4S) at L of 10^{34} produce 2×10^8 B's per 10^7 s.
- ◆ B_s & Λ_b and other b-flavored hadrons are accessible for study at the Tevatron.
- ◆ Charm rates are $\sim 10x$ larger than b rates

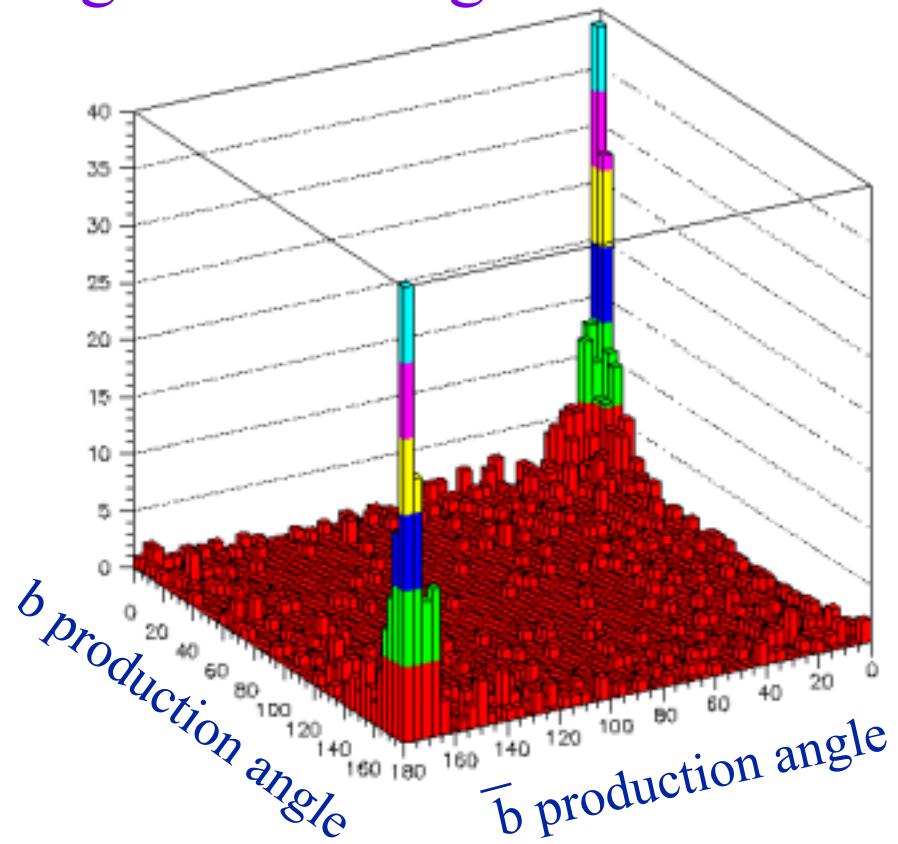


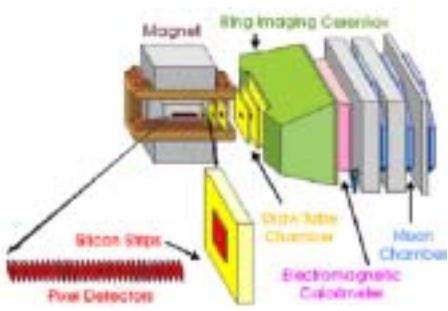
Characteristics of hadronic b production

The higher momentum b's are at larger η 's

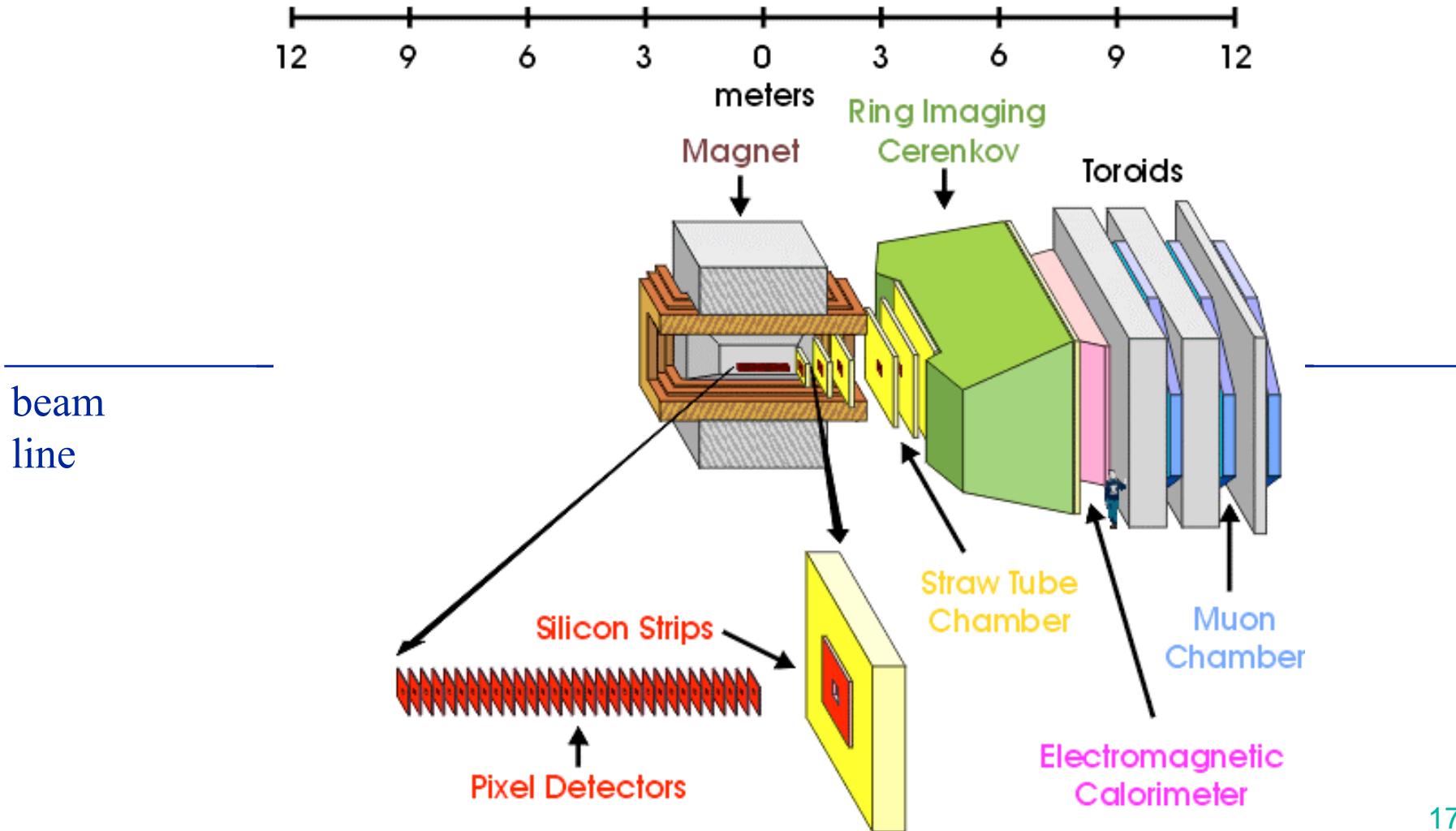


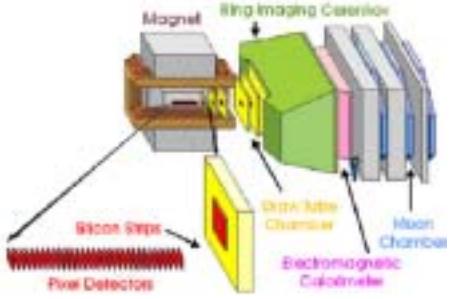
b production peaks at large angles with large $\bar{b}b$ correlation





The BTeV Detector

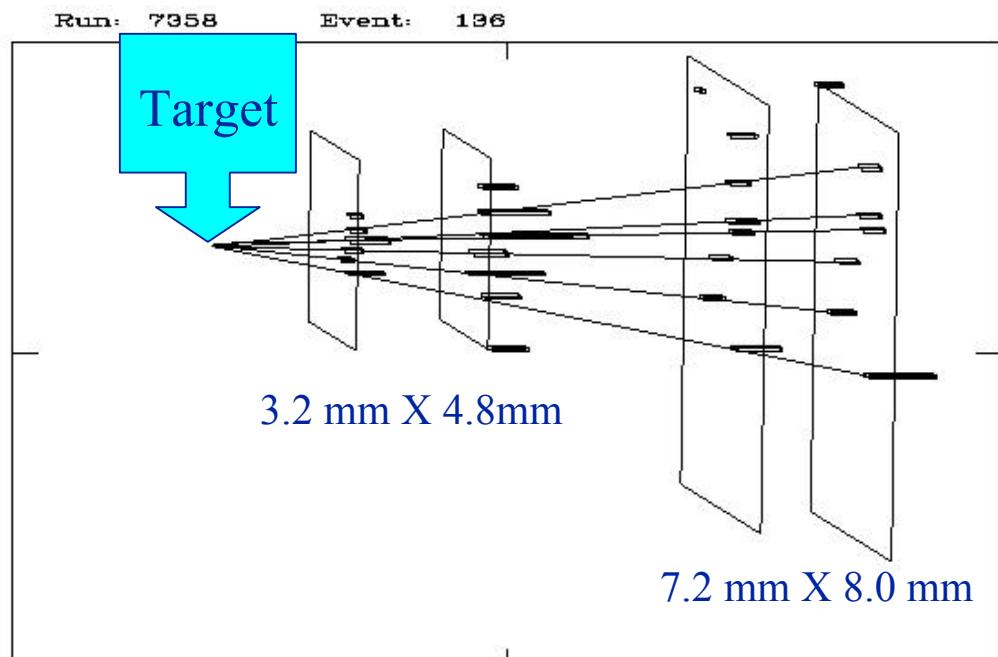


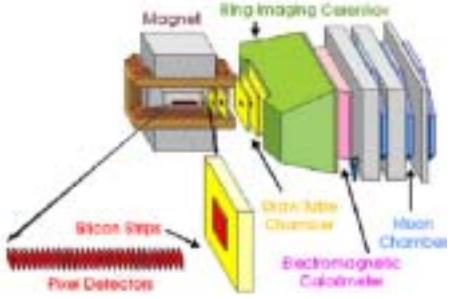


Physics Simulations Tools

Full GEANT has multiple scattering, bremsstrahlung, pair conversions, hadronic interactions and decays in flight; smears hits and refits the tracks using “Kalman Filter.” No pattern recognition (except for trigger). However, we do not expect large pattern recognition problems

**This track density
is 10x higher than
what is expected in
BTeV!**



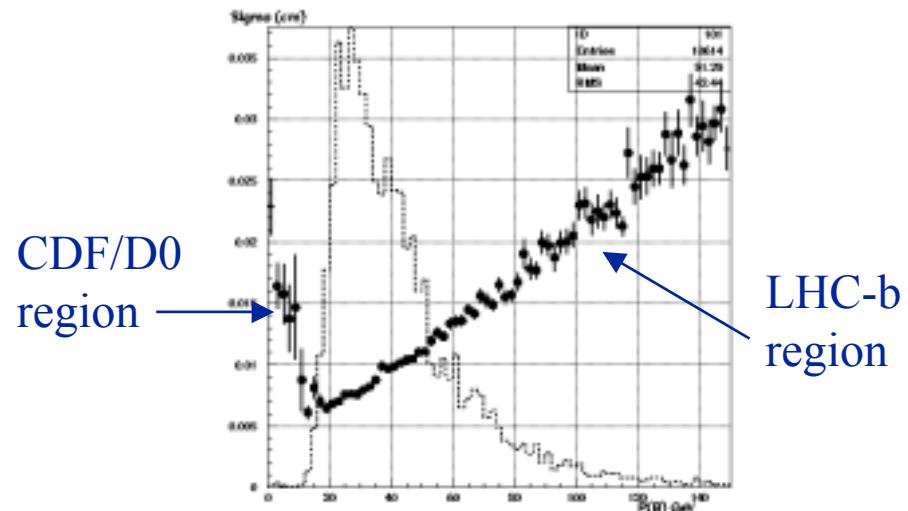
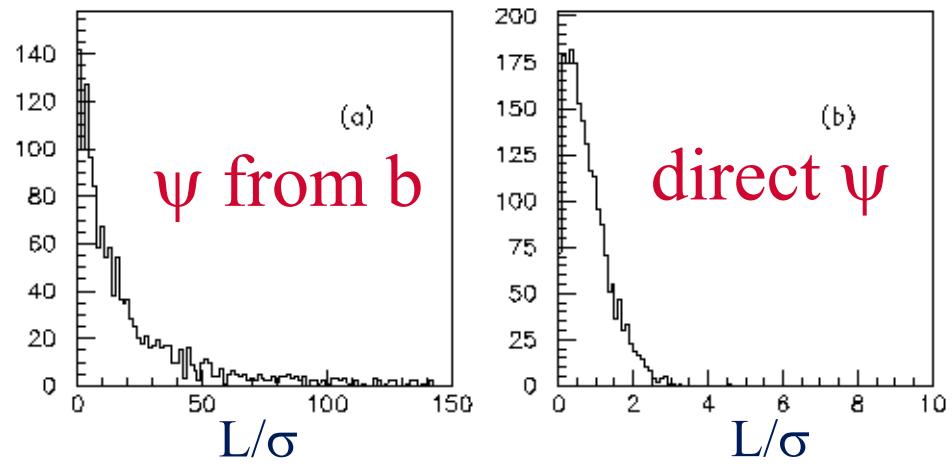


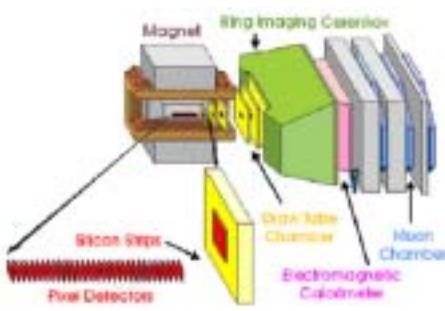
Fundamentals: Decay Time Resolution

- ◆ Excellent decay time resolution
 - ◆ Reduces background
 - ◆ Allows detached vertex trigger
- ◆ The average decay distance and the uncertainty in the average decay distance are functions of B momentum:

$$\langle L \rangle = \gamma \beta c \tau_B$$

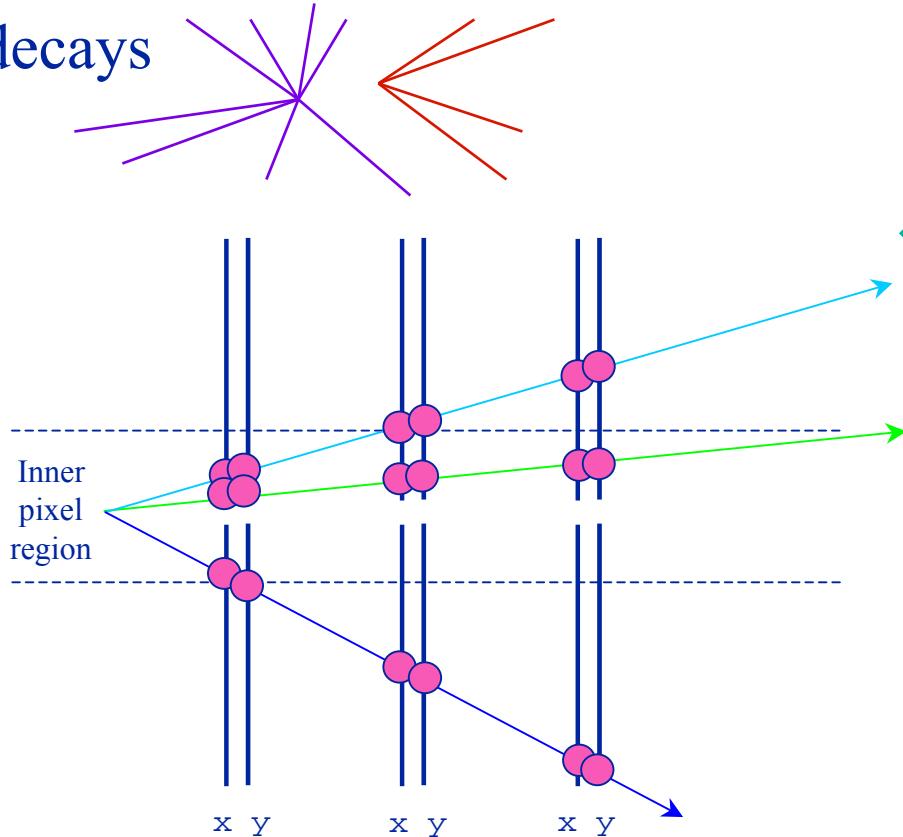
$$= 480 \text{ } \mu\text{m} \times p_B/m_B$$



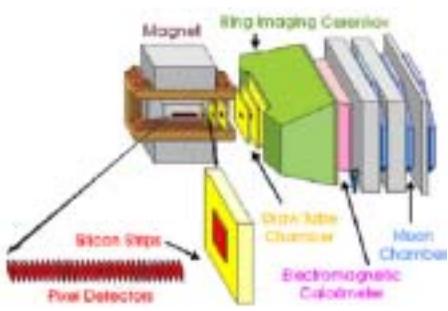


Pixel Trigger Overview

- ◆ Idea: find primary vertices & detached tracks from b or c decays

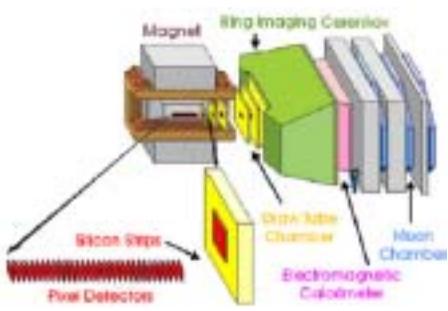


- ◆ Pixel hits from 3 stations are sent to an FPGA tracker that matches “interior” and “exterior track hits”
- ◆ Interior and exterior triplets are sent to a farm of DSPs to complete the pattern recognition:
 - interior/exterior triplet matcher
 - fake-track removal



Detached Vertex Trigger

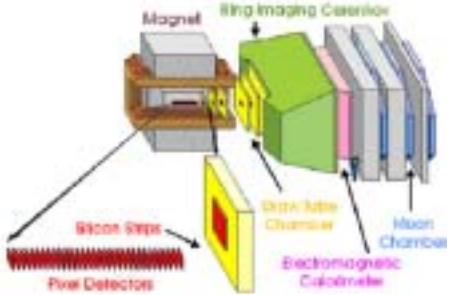
- ◆ Level I Trigger uses information from the Pixel Detector to find the primary vertex and then look for tracks that are detached from it
- ◆ The simulation does the pattern recognition. It uses hits from GEANT including multiple scattering, bremsstrahlung, pair conversions, hadronic interactions and decays in flight
- ◆ Detailed studies of efficiency and rejection for up to an average of three interactions/crossing



Trigger Performance

- ◆ For a requirement of at least 2 tracks detached by more than 4σ , we trigger on only 1% of the beam crossings and achieve the following efficiencies for these states:

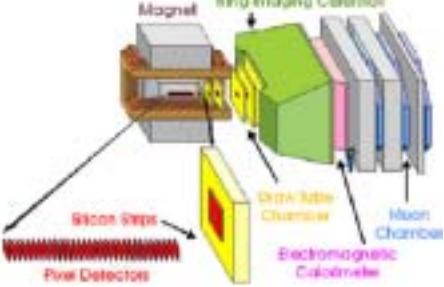
State	efficiency(%)	state	efficiency(%)
$B \rightarrow \pi^+ \pi^-$	55	$B^0 \rightarrow K^+ \pi^-$	54
$B_s \rightarrow D_s K$	70	$B^0 \rightarrow J/\psi K_s$	50
$B^- \rightarrow D^0 K^-$	60	$B_s \rightarrow J/\psi K^*$	69
$B^- \rightarrow K_s \pi^-$	40	$B^0 \rightarrow K^* \gamma$	40



A sample calculation:

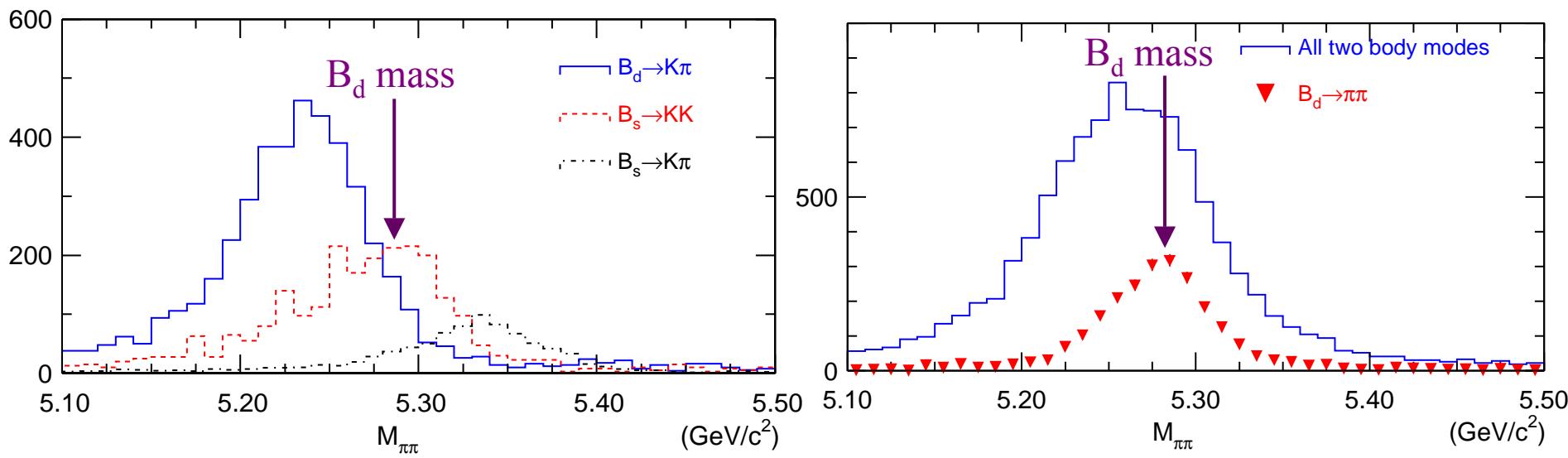
$$B^0 \rightarrow \pi^+ \pi^-$$

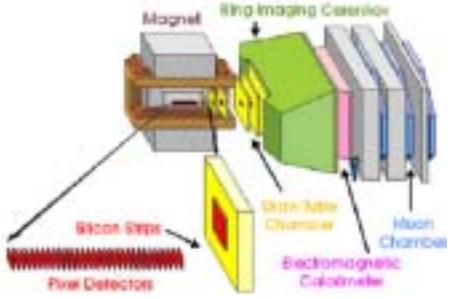
Cross-section	$100 \mu b$
Luminosity ($\langle \sigma \rangle$ interactions/crossing)	2×10^{32}
# of B^0 /Year (10^7 s)	1.5×10^{11}
$B(B^0 \rightarrow \pi^+ \pi^-)$	0.45×10^{-5}
Reconstruction efficiency	0.04
Particle I.D. efficiency	0.82
Triggering efficiency (after all other cuts)	0.55
L1+L2	
# ($\pi^+ \pi^-$)	12,200
ϵD^2 for flavor tags (K^\pm, ℓ^\pm , same + opposite side jet tags)	0.1
# of tagged $\pi^+ \pi^-$	1,220
Signal/Background	3
Error in $\pi^+ \pi^-$ asymmetry (including bkgrd)	± 0.033



$B^0 \rightarrow \pi^+ \pi^-$ Analysis: The Importance of Particle ID

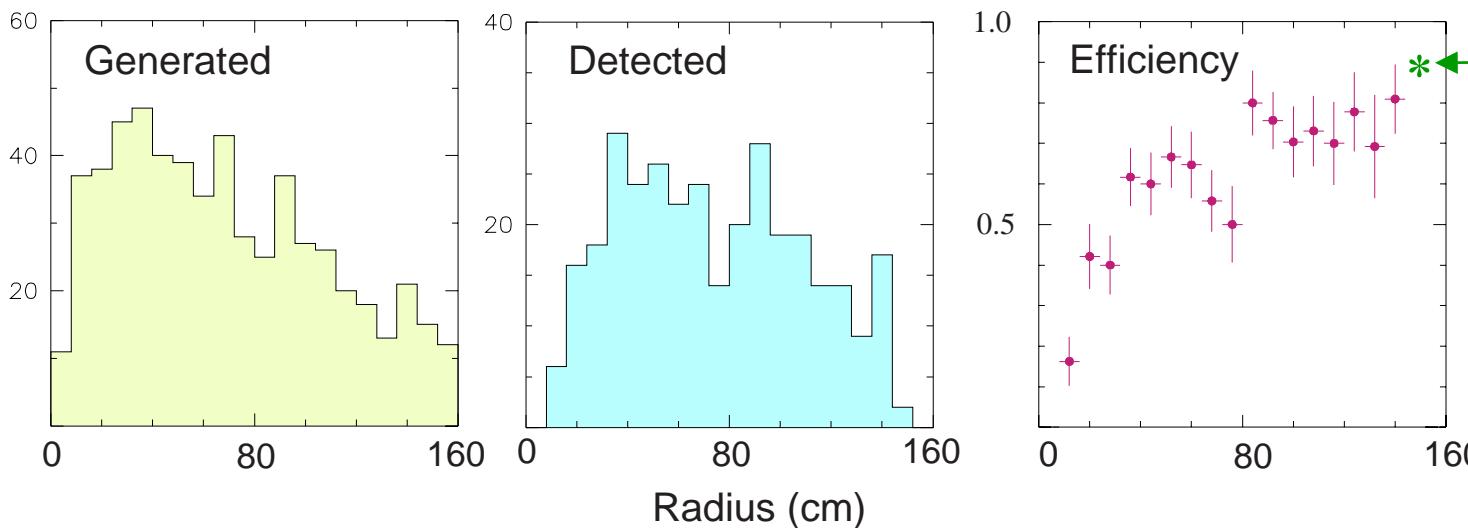
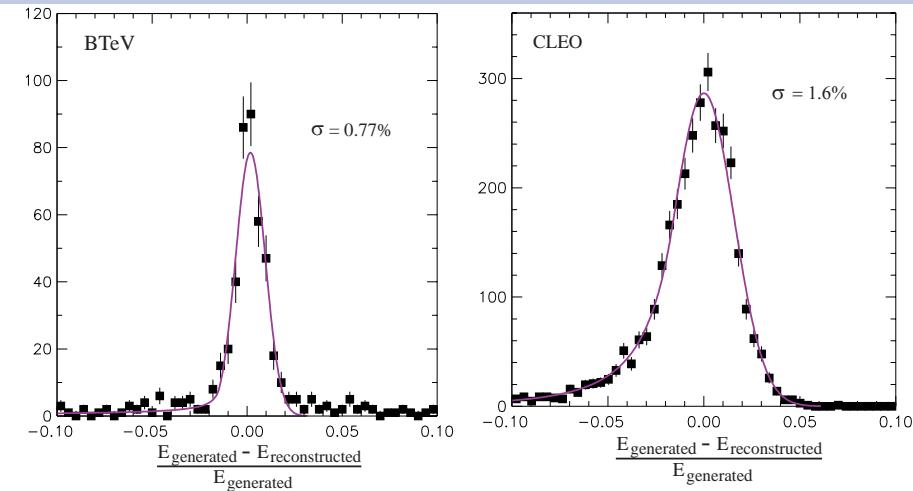
- ◆ Require that each π be properly identified in the RICH. Otherwise the measurement is probably impossible.

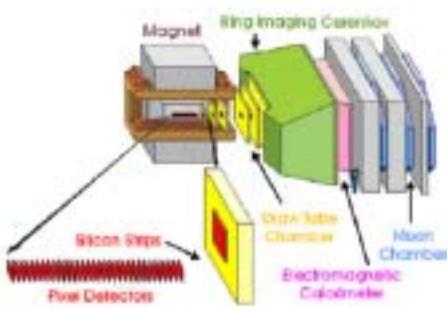




EM calorimetry using PbWO_4 Crystals

- ◆ GEANT simulation of $B^0 \rightarrow K^* \gamma$, for BTeV & CLEO
- ◆ Isolation & shower shape cuts on both



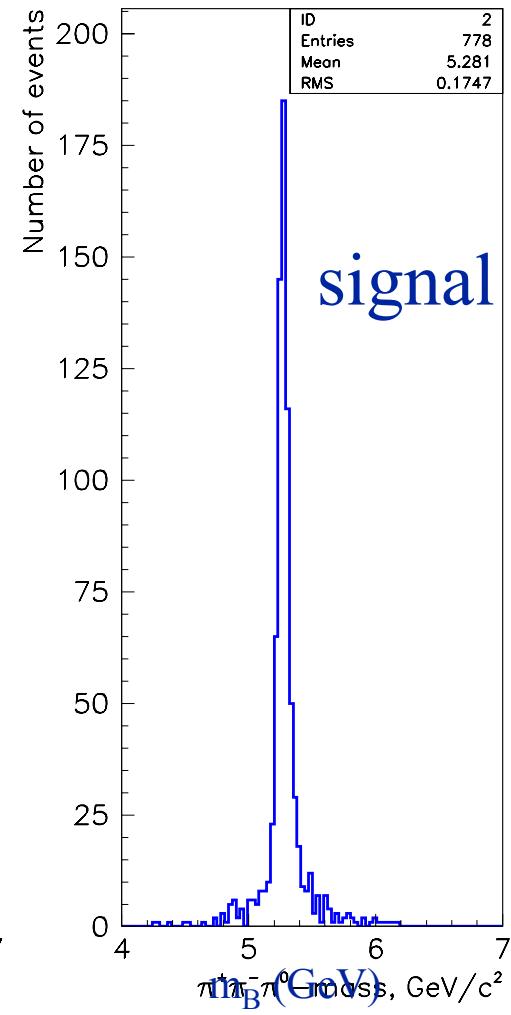
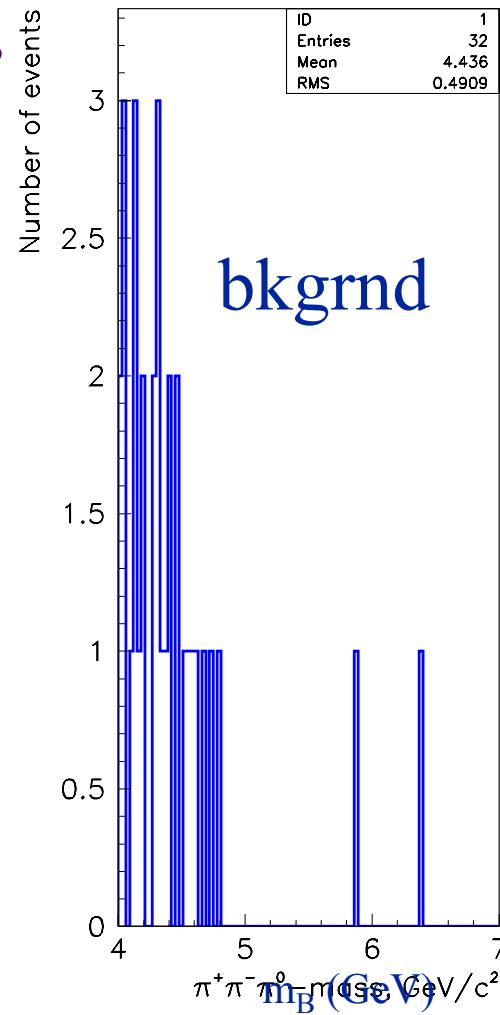
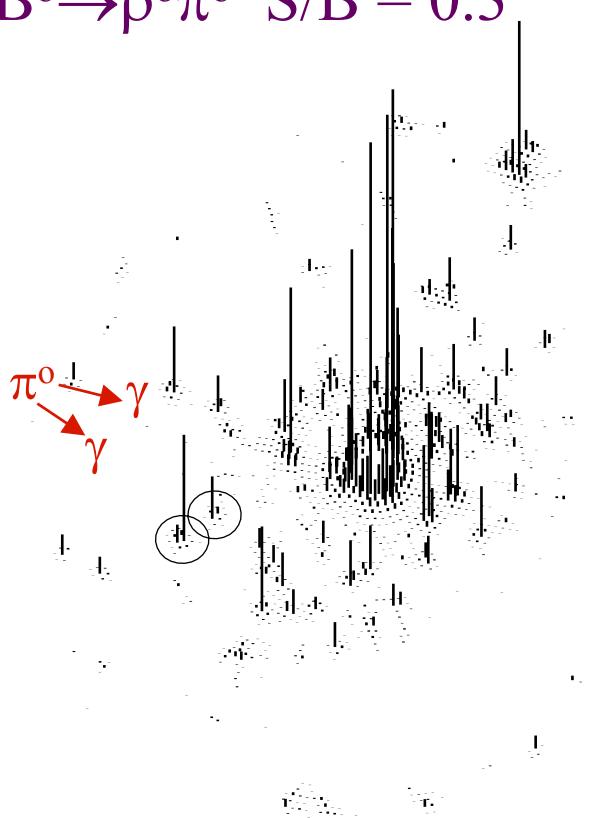


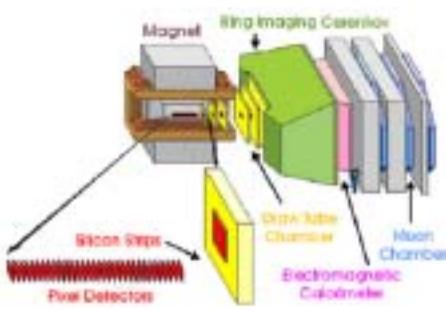
$B^0 \rightarrow \rho \pi$

Based 9.9×10^6 bkgrnd events

$B^0 \rightarrow \rho^+ \pi^-$ S/B = 4.1

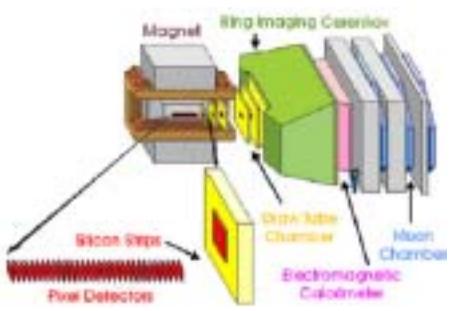
$B^0 \rightarrow \rho^0 \pi^0$ S/B = 0.3





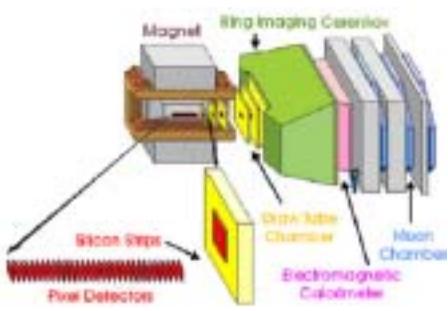
Physics Reach (CKM) in 10^7 s

Reaction	$B(B)(x10^{-6})$	# of Events	S/B	Parameter	Error or (Value)
$B^0 \rightarrow \pi^+ \pi^-$	4.5	14,600	3	Asymmetry	0.030
$B_s \rightarrow D_s K^-$	300	7500	7	γ	8°
$B^0 \rightarrow J/\psi K_S$ $J/\psi \rightarrow \ell^+ \ell^-$	445	168,000	10	$\sin(2\beta)$	0.017
$B_s \rightarrow D_s \pi^-$	3000	59,000	3	x_s	(75)
$B^- \rightarrow D^0 (K^+ \pi^-) K^-$	0.17	170	1		
$B^- \rightarrow D^0 (K^+ K^-) K^-$	1.1	1,000	>10	γ	13°
$B^- \rightarrow K_S \pi^-$	12.1	4,600	1		$<4^\circ$ +
$B^0 \rightarrow K^+ \pi^-$	18.8	62,100	20	γ	theory errors
$B^0 \rightarrow \rho^+ \pi^-$	28	5,400	4.1		
$B^0 \rightarrow \rho^0 \pi^0$	5	780	0.3	α	$\sim 4^\circ$
$B_s \rightarrow J/\psi \eta$, $J/\psi \rightarrow \ell^+ \ell^-$	330	2,800	15		
$B_s \rightarrow J/\psi \eta'$, $J/\psi \rightarrow \ell^+ \ell^-$	670	9,800	30	$\sin(2\chi)$	0.024



Physics Reach Rare Decays

Reaction	$B(10^{-6})$	Signal	S/B	Physics
$B^0 \rightarrow K^{*0} \mu^+ \mu^-$	1.5	2530	11	polarization & rate
$B^- \rightarrow K^- \mu^+ \mu^-$	0.4	1470	3.2	rate
$b \rightarrow s \mu^+ \mu^-$	5.7	4140	0.13	rate: Wilson coefficients



Comparisons With Current e^+e^- B factories

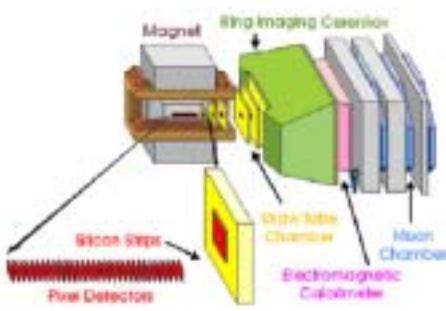
- ◆ Number of flavor tagged $B^0 \rightarrow \pi^+ \pi^-$ ($B=0.45 \times 10^{-5}$)

	L (cm $^{-2}$ s $^{-1}$)	σ	# $B^0/10^7$ s	ε	εD^2	#tagged
e^+e^-	10^{34}	1.1 nb	1.1×10^8	0.45	0.26	56
BTeV	2×10^{32}	100 μ b	1.5×10^{11}	0.021	0.1	1426

- ◆ Number of $B^- \rightarrow \bar{D}^0 K^-$ (Full product $B=1.7 \times 10^{-7}$)

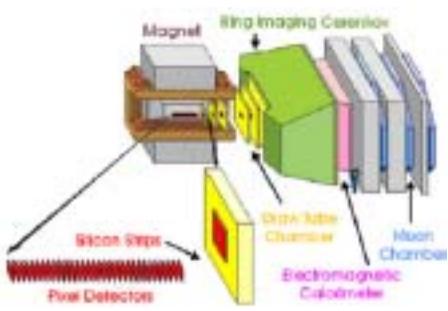
	L (cm $^{-2}$ s $^{-1}$)	σ	# $B^0/10^7$ s	ε	#
e^+e^-	10^{34}	1.1 nb	1.1×10^8	0.4	5
BTeV	2×10^{32}	100 μ b	1.5×10^{11}	0.007	176

- ◆ B_s , B_c and Λ_b not done at Y(4S) e^+e^- machines



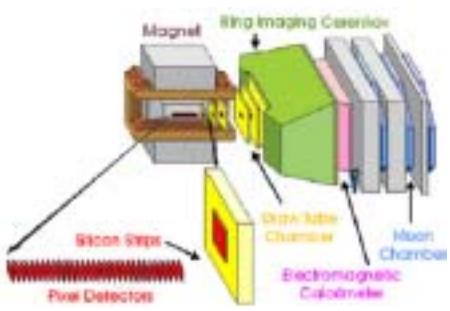
Reconstructed Events in New Physics Modes: Comparison of BTeV with B-factories

Mode	BTeV (10^7 s)			B-fact (500 fb^{-1})		
	Yield	Tagged	S/B	Yield	Tagged	S/B
$B_s \rightarrow J/\psi \eta^{(\prime)}$	12650	1645	>15	-	-	
$B^- \rightarrow \phi K^-$	11000	11000	>10	700	700	4
$B^0 \rightarrow \phi K_s$	2000	200	5.2	250	75	4
$B^0 \rightarrow K^* \mu^+ \mu^-$	2530	2530	11	~ 50	~ 50	3
$B_s \rightarrow \mu^+ \mu^-$	6	0.7	>15	0		
$B^0 \rightarrow \mu^+ \mu^-$	1	0.1	>10	0		
$D^{*+} \rightarrow \pi^+ D^0, D^0 \rightarrow K \pi^+$	$\sim 10^8$	$\sim 10^8$	large	8×10^5	8×10^5	large



Advantages of BTeV with respect to LHCb

- ◆ BTeV has vertex detector in magnetic field which allows rejection of high multiple scattering (low p) tracks in the trigger
- ◆ BTeV is designed around a pixel vertex detector which has much less occupancy, and allows for a detached vertex trigger in the first trigger level.
 - ◆ Important for accumulation of large samples of rare hadronic decays and charm physics.
 - ◆ Allows BTeV to run with multiple interactions per crossing, L in excess of $2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$
- ◆ BTeV will have a much better EM calorimeter
- ◆ BTeV is planning to read out 5x as many b's/second

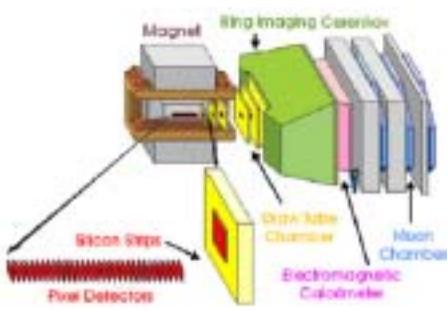


Specific Comparisons with LHC-b III

Yields in two final states

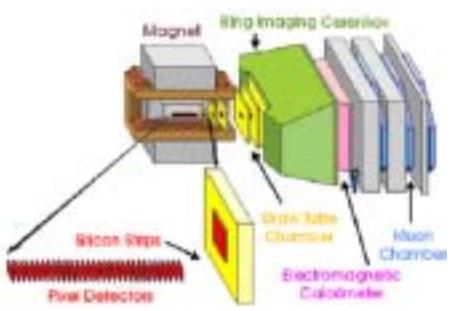
Mode	BR	BTeV		LHC-b	
		Yield	S/B	Yield	S/B
$B_s \rightarrow D_s K^-$	3.0×10^{-4}	7530	7	7660	7
$B^0 \rightarrow \rho^+ \pi^-$	2.8×10^{-5}	5400	4.1	2140	0.8
$B^0 \rightarrow \rho^0 \pi^0$	0.5×10^{-5}	776	0.3	880	not known

We cannot afford to degrade detector performance by much



Conclusions

- ◆ We are very excited about this experiment and are eager to get going
- ◆ Next Joel will describe the detector and costing issues



The End